From Z-Machines to ALMA: (Sub)millimeter Spectroscopy of Galaxies
ASP Conference Series, Vol. TBD, 2006
A. J. Baker, J. Glenn, A. I. Harris, J. G. Mangum, and M. S. Yun, eds.

Z-machine science other than CO – scientific and technical prospects for very wide band-width radio and (sub)millimeter-wavelength spectroscopy

Karl M. Menten

Max-Planck-Institut für Radioastronomie

Abstract. While clearly the main scientific targets of "z-machines" will be redshifted lines of carbon monoxide, there also exist other interesting applications. Here scientific and technological aspects of observing lines from CO and other species at high redshift and in the local universe are discussed as are the limitations of such efforts and prospects for the future.

1. Introduction

At present, several concepts for "z-machines" – detector/spectrometer combinations covering wide spectral ranges – are discussed for different wavelength regimes. Systems presented at this workshop are summarized in Table 1. Any

Table 1. Z-machines currently under discussion

System	Frequency range	Velocity Resolution[a]	Telescope[b]
Zpectrometer[c]	28.5 – 34.5 GHz	150 km s^{-1}	GBT[d]
RSR[e]	74 – 110 GHz	100 km s^{-1}	LMT[f]
Zspec[g]	185 – 293 GHz	800 km s^{-1}	(sub)mm telescopes
ZEUS[h]	various submm bands	300 km s^{-1}	submm telescopes

[a]Velocity resolutions vary over/with band. [b]All instruments can be adapted to various telescopes suitable for their wavelength range. [c]Harris et al. (these proceedings). [d]Green Bank Telescope [e]Redshift Search Receiver; see Erickson et al. (these proceedings). [f]Large Millimeter Telescope – Gran Telescopio Milimétrico [g]Glenn et al. (these proceedings). [h]The Redshift(z) and Early Universe Spectrometer; see Stacey et al. (these proceedings).

search for extremely weak radio or (sub)millimeter (submm) high-z line emission requires considerable investment in observing time. We therefore start (in §2.) by summarizing high-z cm and mm spectroscopy. In particular we discuss the pros and cons of building z-machines in the centimeter range, i.e. to search for low rotational quantum number ($J_{\rm upper} = 1$ or 2) carbon monoxide (CO) and (in §2.2.) hydrogen cyanide (HCN) transitions.

Largely because of their relatively coarse velocity resolution, for all the z-machines under discussion meaningful observations of the local universe are

restricted to extragalactic astronomy, i.e. spectroscopic observations of nearby galaxies. In §3. we see that there is indeed very interesting science to be explored.

Limitations to attempts at detecting very weak, broad line emission are discussed in §4. together with methods to overcome them. We point out the need for wide instantaneous bandwidth, high spectral resolution (= large channel number) detector/spectrometer combinations.

In §5. we present a novel spectrometer concept, the Fast Fourier Transform Spectrometer and we argue that, rather than building low resolution spectrometers, a very wide-band receiver together with such a very high resolution spectrometer would allow, in addition to extragalactic science, fantastic galactic astronomy, examples of which are briefly presented in §5.1.

2. High-z z-machine science

2.1. CO

Over the last few years, redshifts of many high-z submillimeter dust emission ("SCUBA") sources have been measured by optical spectroscopy using large telescopes (Chapman et al. 2003, 2005) allowing searches for mm-wavelength lines (mostly from CO), which frequently are successful (see contributions by Cox and Weiß to these proceedings).

In some cases the redshifts delivered by optical spectroscopy can be different by the equivalents of hundreds of km s^{-1} from the CO redshifts. This presents a problem for the relatively narrow band-passes of the most prolific telescope for detecting such sources, the IRAM Plateau de Bure Interferometer (PdBI). However, this situation will be remedied in the near future, by a refurbishing with broader intermediate frequency (IF) band receivers and a broader band correlator and wouldn't motivate the need for a z-machine.

Despite much progress, about a third of all SCUBA sources remain unidentified at other wavelengths. Since their non-discovery at optical or even near-infrared wavelengths may mean that these objects have immense amounts of dust and, thus, extremely high star formation rates, determining their redshifts and, thus, their luminosities, is of great interest. For this (sub)mm observations are invaluable as optical/ultraviolet observations are heavily biased by dust obscuration.

For such objects photometric methods using the radio-to-infrared relation result in crude redshift estimates (Carilli & Yun 1999, 2000; Hughes et al. 2002; Aretxaga et al. 2003 and these proceedings). Obtaining accurate redshifts and, thus, CO luminosities are main motivations for z-machines.

Z-machines in the centimeter range, in particular in the K- and Ka-bands (18 – 26.5 and 26.5 – 38 GHz, respectively) are partially motivated by the desire to probe CO distributions similar to those that constitute the large-scale molecular gas in "normal" galaxies ($J_{\rm upper} \sim 3$) . Over most of the Milky Way the $J = 3 - 2$ transition has the highest emissivity, except for the central few degrees in which the $J = 4 - 3$ and $5 - 4$ lines dominate (Bennett et al. 1994). This extended gas is significantly cooler ($\sim 10 - 20$ K) than the > 60 K warm interstellar medium (ISM) probed by the mid- and higher J lines

($J = 4, 5, 6, 7 \ldots$) that are shifted to mm-wavelengths and sample starburst regions and/or the vicinities of active galactic nuclei (AGN).

Recently, the CO $J = 1-0$ line was discovered with the Green Bank Telescope (GBT) and the Effelsberg 100 m telescope toward three $z > 4$ objects, the QSOs BR 1202-0725 (z=4.7), PSS J2322+1944 (z=4.1), and APM 08279+5255 (z=3.9) (Riechers et al. 2006 and these proceedings). These observations required dozens of hours of telescope time. Comparing their $J = 1-0$ results with those obtained for higher-J lines, Riechers et al. conclude that all are consistent with a single (warm) gas component that well explains the observations for a wide range of J (up to $J_{\rm upper} = 11$; see Weiß et al. these proceedings and in preparation). These result seem to discourage $J = 1-0$ searches, which are quite expensive compared to searches for higher-J transitions[1]. However, we note that this conclusion so far only holds for the few sources intensely studied: the three sources mentioned above and the radio galaxy 4C 60.07 (Greve et al. 2004), which all contain strong AGN and for the Extremely Red Object (ERO) J164502+4626.4, which possibly also contains an AGN (Greve et al. 2003). The situation might be different for non-AGN dominated submillimeter galaxies.

We also note that, Australia Telescope Compact Array (ATCA) results for the radio galaxy TN J0924-2201 seem to indicate that the CO $J = 1-0$ and $5-4$ emissions associated with this object arise from different locations that are separated by ~ 50 kpc (Klamer et al. 2005).

By far the most powerful instrument to detect and image lower-J CO will be the Expanded Very Large Array (EVLA)[2] which will complement higher-J CO observations made with the Atacama Large Millimeter Array (ALMA). The EVLA will have an 8 GHz IF bandwidth at the K- and $Q-$bands (19 – 50 GHz). A first glimpse at the EVLA's promise were recent VLA observations that resulted in the first resolved CO images a high redshift object, the $z = 6.42$ SDSS quasar J1148+5251 (Walter et al. 2004). While the VLA today has the required sensitivity, these observations suffer from the woefully inadequate bandwidth/channel number combination of the ancient VLA correlator.

While the GBT and the EVLA will have comparable effective collecting areas, EVLA observations will be largely preferable to single dish observations, which will inevitably be limited by baseline quality (see §4.).

Given the timelines for the completion of ALMA and EVLA (early 2010s), single-dish z-machines will be interesting for many years in the interim and it is well worth asking what kind of useful applications they may have other than high-z CO searches (see §3.).

2.2. High-redshift emission from molecules other than CO

Solomon et al. (1992) detected the HCN $J = 1-0$ transition (rest frequency, $\nu_{\rm rest}$, near 88.6 GHz) toward five local ultraluminous infrared galaxies (ULIRGS) and other less luminous systems. They found an average HCN to CO luminosity ratio of 1/6, which is much higher than 1/80, the value found in normal

---

[1] The line flux density increases as ν^2 (i.e., J^2), whereas the detection sensitivity for the higher-J mm observations is only a few times worse than for $J = 1-0$ cm observations

[2] http://www.aoc.nrao.edu/evla/

spiral galaxies. Since the critical density, $n_{\rm crit}$, of this HCN line is $\sim 10^5$ cm^{-3}, much higher than that of low-J CO lines (hundreds to thousands cm^{-3}), one conclusion was that the relative percentage of dense star-forming gas was significantly higher in ultraluminous systems, which have *bona fide* much higher star formation rates than normal galaxies. For their sample Solomon et al. derived correlations between the far infrared (FIR) luminosity and the HCN luminosity and between the FIR/CO luminosity ratio and the HCN/CO luminosity ratio, which suggest that the latter is a good indicator for star formation activity. Extrapolating to the even higher FIR luminosities of high-z sources one would expect the HCN/CO luminosity ratio to approach one. This trend seems, however, not to continue to higher luminosities (see below).

It should be noted that these results are for the $J = 1-0$ lines of both species. For linear molecules, $n_{\rm crit} \propto J^3\mu^2$, where the electric dipole moment, μ, is 0.11 Debyes for CO and 3.0 D for HCN. For line opacities, $\tau > 1$, $n_{\rm crit}$ is lowered by a factor of $\frac{1}{\tau}$. CO excitation modeling of multi-line high-z datasets indicate substantial opacities for higher-J transitions (many tens to $\sim$ 100), peaking at $J \sim 6$ (Weiß et al. 2006 and these proceedings). For $\tau < 1$ the critical densities of HCN lines would be ≈ 300 times higher than those of CO lines of identical quantum number.

Given the bandwidths of the planned z-machines, for many values of z there will be one or more HCN lines in their bands along with CO lines. So far, high-z HCN $J = 1-0$ emission has been detected only from two sources, both gravitationally lensed: the Cloverleaf quasar (H1413+177) at $z = 2.56$ (Solomon et al. 2003). and IRAS F10214+4724 at $z = 2.29$ (Vanden Bout et al. 2004). Extrapolating to other sources is not straightforward and, given that, both, the Cloverleaf and IRAS F10214+4724 are amongst the strongest higher-z CO sources, that the HCN/CO ($J = 1-0$) luminosity ratio (extrapolated for CO from the $3-2$ line) is very low (0.07 and 0.18, respectively) and that the HCN lines are exceedingly weak ($\sim$ 200 and 450 μJy) the prospects for detecting high-z HCN are not promising for low J values. Indeed do Carilli et al. (2005) not obtain any other clear detection of the $J = 1-0$ HCN line in a sensitive search toward four other high-redshift far-IR-luminous galaxies.

For higher J, on the other hand, at which CO is easier to detect than at low J, the critical densities for HCN excitation are almost certainly prohibitive: $n_{\rm crit}$(HCN) = 8 10^6 cm^{-3} and 1 10^8 cm^{-3} for the $3-2$ and $7-6$ transitions, although these values will be lowered by the fact that HCN lines will also be optically thick. Nevertheless, $n_{\rm crit}$(CO) is only 5 10^4 cm^{-3} and 1 10^6 cm^{-3} for these lines.

To get meaningful input for searches of high-z lines from HCN and other species it would be important to first observe these lines in local ULIRGSs. Given the meager observational situation this is particularly important as signficant variations in relative intensity of the $J = 1-0$ lines of CN and HNC relative to HCN $1-0$ have been reported in a sample of infrared-luminous galaxies (Aalto et al. 2002) with HCN intensities generally stronger, but frequently not much stronger, than HNC and CN intensities.

As to molecules other than CO, HCN, HNC, and CN, as discussed at the end of §3., available observations of local starbursts do not give reason for optimism as to their detectability at high redshift.

2.3. Carbon (CI and CII)

Neutral atomic carbon (CI) has two submillimeter-wavelength fine structure lines: ${}^3P_1 -{}^3 P_0$ ($\nu_{\rm rest}$ near 492 GHz) and ${}^3P_2 -{}^3 P_1$ ($\nu_{\rm rest}$ near 809 GHz). The lower frequency line has now been detected in three $z = 2.3 - 2.5$ sources, including the Cloverleaf (Barvainis et al. 1987; Weiß et al. 2003). The 809 GHz line so far has only been detected in the latter (Weiß et al. 2003) in which both lines have more than 2 times lower flux density than the CO $J = 3 - 2$ line. If, as is likely, in other sources the flux densities of the CI lines also are lower than those of CO lines, the former are not interesting as redshift beacons for z-machines. However, given the frequencies of the CO $J = 4-3$ and $8-7$ lines (461 and 897 GHz, respectively) any z-machine detecting one of these CO lines is also likely to detect a CI line for free.

In contrast to the CI lines, which essentially sample the same gas as CO, i.e., molecular clouds, the 158 μm (1900 GHz) ${}^2P_{3/2} -{}^2 P_{1/2}$ fine structure line of ionized carbon (CII) arises from the more extended ISM. It is the most luminous cooling line in the ISM of the Milky Way and other low to moderate luminosity galaxies with FIR luminosities, $L_{\rm FIR}$, $< 10^{12} L_\odot$ (e.g., Stacey et al. 1991; Malhotra et al. 2001). In such systems, this line's luminosity, $L_{\rm CII}$, contributes between 0.1 and 1% of $L_{\rm FIR}$. For more luminous galaxies (ULIRGs) ISO observations show that the relative contribution of $L_{\rm CII}$ to $L_{\rm FIR}$ is about an order of magnitude smaller (e.g. Luhman et al. 2003; see Maiolino et al. 2005 for a discussion of possible explanations). For $z > 6.0$ the line gets redshifted to 270 GHz, the upper cut-off of the IRAM 30m telescope's 1.3 mm receiver. Maiolino et al. (2005) made the first high-z detection of this line toward J1148+5251 at $z = 6.42/256.2$ GHz, which would be within the range of Zspec.

Today (before the ALMA era) it is only possible to observe the CII line from the ground for $z > 6.0$. This is because doing so requires the largest collecting area telescopes (IRAM 30m and PdBI) under exceptional weather conditions. With its much larger collecting area and far better site, ALMA will make lower-z CII observations possible in higher frequency submm windows.

Observations of the CII line clearly are of paramount importance for a characterization of the emitting sources' ISM. However, as to the potential of CII searches for redshift determination, unless there are sources with much larger $L_{\rm CII}/L_{\rm FIR}$ (and larger $L_{\rm CII}/L_{\rm CO}$) ratios than known today (which is not impossible) it is far less expensive to search for CO lines at lower frequencies (e.g. with the RSR) for this purpose.

3. Extragalactic interstellar medium chemistry

Since the late 1980s Mauersberger & Henkel and their collaborators have detected (mostly with the IRAM 30m telescope) a large number of molecules toward the nuclei of nearby galaxies Species include CH_3OH, CN, C_2H, HCN, HNC, HCO^+, HC_3N, CS, N_2H^+, SiO, HNCO, CH_3CCH, CH_3CN, SO_2, NS, NO, H_2CO, and NH_3. These (or a selection of these) molecules are found toward the nuclear regions of NGC 253, IC 342, NGC 6946, M82, NGC 4945, NGC 6946, Maffei 2, i.e. mostly starburst galaxies. For many species rare isotopomers are detected and for some multi-transition studies afford excitation

analyses. Except for NH_3, most of the observations were made in the 3 and 2 mm ranges and sampled low-J lines for diatomic and linear species.

The nearby ($D \sim 3$ Mpc) starburst galaxy NGC 253's chemistry was studied in most detail. Martin et al. (2006) scanned most of the 2 mm window (129.1 to 175.2 GHz) and discovered 111 emission features from 25 molecular species. They find that "the chemistry of NGC 253 shows a striking similarity with the chemistry observed toward the Galactic center molecular clouds, which are thought to be dominated by low-velocity shocks. This resemblance strongly suggests that the heating in the nuclear environment of NGC 253 is dominated by the same mechanism as that in the central region of the Milky Way." Martin et al. also emphasize similarities between the chemistry of NGC 253 and IC 342 and NGC 4945 and pronounced differences to that of M82. All in all these studies

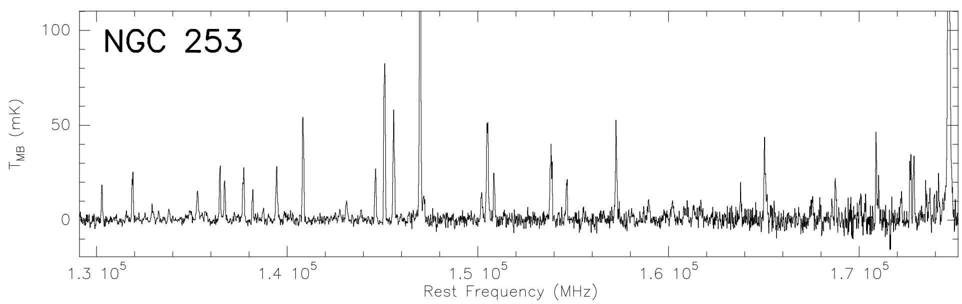

Figure 1. The 129.1 to 172.2 GHz range spectrum of the central region of NGC 253. This spectrum was "mosaiced" from a total of 46 individual spectra. The channel spacing is 69 km s^{-1}.

(and studies of our own Galactic center at much higher physical resolution) provide a fascinating way to probe lower luminosity versions of the starburst cores of ULIRGs, local and at high redshift.

Let us check the suitability of the z-machines in Table 1 for studies such as these. Martin et al. smoothed their final spectrum to a resolution of 69 km s^{-1} and even a factor of 2 lower resolution would be adequate to avoid line blending. Such resolutions could be easily afforded by a 2 or 3 mm version of the Zpectrometer or by the RSR. Zspec, on the other hand, would have severe line blending problems due to its coarse (~ 800 km s^{-1}) resolution.

The observing time requirements of the NGC 253/IRAM 30m line survey were completely dictated by the available receiver/spectrometer equipment: 2 SIS receivers with 1 GHz bandwidth each operated in parallel. HEMT receivers with competitive noise performance will be available soon at these wavelengths and a single one would cover the whole 46 GHz bandwidth instantaneously, reducing the observing time from ca. 50 h to just two. Similar arguments hold for the 3 mm band already now. This means that extremely exciting science of this kind could be done with the RSR now and in the 2 mm band with a future HEMT receiver on a large number of and/or weaker sources.

Detecting lines from the molecules observed in NGC 253 in high-z sources seems prohibitive, however. Just note that the strongest line in the NGC 253 2 mm survey (CS $J = 3 - 2$) has a peak flux density of ca. 0.5 Jy. It is ca. 40 times weaker than the CO $J = 1 - 0$ line toward the same region (spectrum presented by Ott et al. 2005), which has a flux density of ca. 20 Jy!

4. Getting flat baselines

Given that that many instrumental and atmospheric sources of error are uncorrelated between its unit telescopes, an interferometer naturally provides high quality spectral baselines (provided the passband is calibrated). In contrast, the baseline quality of spectra obtained with single dish telescopes are frequently compromised for a number of reasons such as power level variations between on and off source scans or reflections by feed structures. Although the GBT's unblocked aperture should minimize the latter, baseline problems nevertheless persevere (see Hainline & Blain, these proceedings) unless special steps are taken.

An ingenious concept consisting of a set of analog lag cross-correlation spectrometers combined with a multi-channel correlation radiometer aims to overcome these problems in the case of the Zpectrometer (Harris et al., these proceedings), while the RSR employs a dual beam switching scheme and a Faraday rotation switch allowing very fast (1 kHz) switching between the beams (Erickson et al.; these proceedings.)

For (sub)millimeter telescopes a breakthrough in baseline quality (and huge improvements in overall observing quality and efficiency) was achieved by the installation of "wobbling" subreflectors that "chop" between the target and an off position (typically a few FHWM beam diameters away) on a > 1 Hz cycle. Recent extensive multi-high-J high-z CO line observations with the IRAM 30 m telescope have resulted in a large number of spectra whose excellent quality was verified by comparison with spectra obtained with the PdBI (Weiß et al. 2005a,b and these proceedings).

Because of their large size and weight, it may not be possible to wobble secondaries of the large centimeter-wavelength telescopes and special solutions as those described above may be required. Also, adaptive, deformable secondaries, an example of which will be installed at the Effelsberg telescope soon, should improve overall data quality.

Nevertheless, at mm-wavelengths single-dish chopped observations yield baselines that are flat over velocity ranges that are larger than the linewidths of galaxies and very wideband observations should be possible with HEMT receivers. Special purpose designs such as the Zpectrometer's, Zspec's and the RSR's certainly hold great promise. However, these instruments are hardwired to certain frequency ranges and have a fixed, coarse velocity resolution.

Rather than building special purpose, low resolution spectrometers, in the following we strongly advocate to do the opposite, i.e. to build high resolution, universally usable devices that cover very wide bands and can be employed in *any* wavelength region. These are just becoming available in the form of Fast Fourier Transform Spectrometers (see below).

5. Fast Fourier Transform Spectrometers

Progress in digital electronics has resulted in an exciting new spectrometer concept: The Fast Fourier Transform Spectrometer (FFTS). In an FFTS a receiver's IF band is directly sampled with 8/10 bit resolution using commercially available analog-to-digital converters. Because of the high resolution, the "spectrometer efficiency", $\eta_{\rm S}$, in the radiometer equation becomes 1. This brings a factor ≈ 1.5

improvement in integration time compared to 2 bit/3 level autocorrelators, for which $\eta_S \approx 1.23$. The FFT is continuously performed with a chosen window function, which can be selected to suppress spectral side lobes ("ringing" caused by Gibbs' phenomenon). Thus, FFTSs have a much higher dynamic range than most other spectrometers. In addition, FFTSs do not need total power detectors and leveling the power levels is much simpler than in an autocorrelator. This results in a considerable simplification of a receiver's IF section.

The FFT, as well as power spectrum averaging, is performed in one complex logic chip, a Field-Programmable Gate Array (FPGA). Autocorrelators, in contrast, need cascaded, custom chips, making their design and production much more complex and expensive.

FPGA chips have a remarkable degree of integration: *Everything*, the complete spectrometer (digital filters, windows, FFT, power builder, and accumulator) is on one chip.

That the chips are mass-produced rather than custom-designed as for correlators, makes large bandwidth FFTSs relatively affordable. In addition, it allows a much better reaction to the market, taking full advantage of Moore's law. In addition, the software for FPGA programming can be purchased "off the shelf".

FFTSs afford very high channel numbers, 32768 channels per 1 GHz (in early 2006), with twice the bandwidth and twice the number of channels for the same price (ca. 20000 kEuros) available soon. This prize is expected to come down by a factor > 5 for institutions who learn to program the FPGAs and design their own boards themselves, also taking advantage of a growing demand from industry, which leads to higher chip production rates. The very high channel numbers, while uninteresting for extragalactic astronomy (except for maser searches), make FFTs highly attractive allround devices fulfilling the needs for instantaneous coverage of wide bands. For example, they are ideally suited for unbiased spectral line surveys of a whole IF band (see §5.1.: At K-band (23 GHz) 1 GHz bandwidth split in 32768 channels gives a velocity resolution of 0.40 km s^{-1}, well suited for many galactic molecular cloud sources. A prototypical narrow band (50 MHz), 1024 channel FFTSs, operated at the Effelsberg 100m telescope is described by Stanko, Klein, & Kerp (2005). A 500 MHz wide/16384 channel FFTS is currently in operation at the 100m telescope.

Benz et al. (2005) describe the architecture and building of a 1 GHz wide/16384 channel FFTS, as well as astronomical observations with it using the KOSMA Gornergrat telescope. A 1 GHz bandwidth/32768 channels FFTS has been installed at the Atacama Pathfinder Experiment (APEX) telescope in mid-2005 and has since been performing flawlessly. There, at 5100 m altitude, another advantage of FFTSs, their modest power consumption, resulting in much easier cooling requirements, certainly adds a significant reliability advantage over autocorrelators.

5.1. Multi-purpose usage of FFTSs

From their concept, FFTSs lend to serilization. Once costs have come down, making large bandwidths economically feasible, a *single* very wideband FFTS will be the spectrometer of choice for many astronomical applications and its use will result in *huge* savings of observing time. For an illustration let us consider

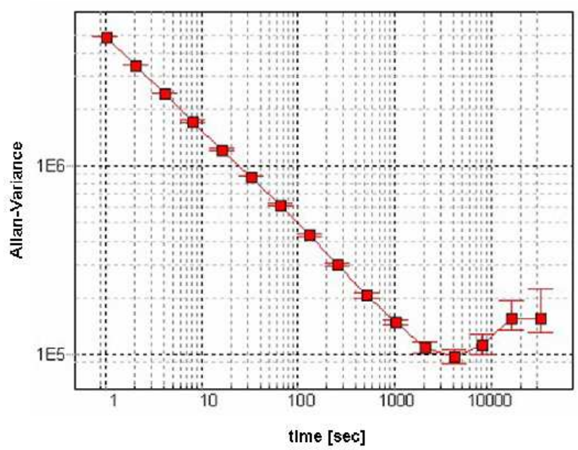

Figure 2. Excellent stability of an MPIfR FFTS: The spectroscopic Allan time (of ca. 4000 seconds!) of two 1 MHz wide channels separated by 600 MHz (see Schieder et al. 1986 for a discussion of the spectroscopic Allan variance). The signal was provided by a temperature-stabilized noise source.

two examples of interesting science in the 3 mm band that would be enabled with an *identical* very wideband FFTS.

Unbiased spectral line surveys Unbiased line surveys are a powerful means to characterize the chemistry of an astronomical source (see §3.). Starting with the Onsala line surveys of the Orion-A star-forming region and the star IRC+10216 (Johansson et al. 1984) the 3 mm band has been surveyed for a number of sources. In a recent survey of the most prolific galactic line source Sgr B2 in the 80 – 116 GHz range with the IRAM 30m telescope more than 4000 spectral features were found (Belloche et al. in prep.). Due to the use of relatively narrowband SIS receivers and limited spectrometer capability (500 MHz wide filterbanks) these observations required a total of 90 single spectra of 20 minutes integration time each (allowing for some overlap). With a wide enough FFTS and a wide bandwidth HEMT receiver the same project would have required a single spectrum.

Multi-molecule large scale mapping It is also worth noting that the 3 mm range contains the ground-state transitions of many important molecules, a.o. CO and its isotopes, HCN, CN, HCO^+, C_2H, and the $J = 2-1$ lines of CS and SiO. Since many of these have large dipole moments and, thus, substantial critical densities, except for very high density/high temperature cores near embedded protostars, only their low-J lines are expected to show spatially extended emission, Within the next few years HEMT focal plane arrays will revolutionize single dish mm- (and cm-)wavelength astronomy. Mapping the emission from the above (and other) molecules, whose larger-scale distribution is poorly known at present, will, a.o., result in the identification of star-forming regions within molecular clouds. Such mapping does of course not require coverage of the whole receiver band, but only, say, ±15 MHz around the frequency of each target line. This

means that for a 100 element array, a total usable bandwidth of 100×30 MHz = 3 GHz is required. If one wanted to image 12 lines simultaneously, one would need an FFTS with 36 GHz bandwidth, identical to the bandwidth one would need for contiguous coverage of the $80 - 116$ GHz range with one element as discussed above. Such mapping would yield an instantaneous chemical fingerprint of large-scale molecular cloud regions.

Acknowledgments. I am grateful to Bernd Klein for comments on the text and discussions on FFTSs (and, above all, to him and his group for building them). I would like to thank Ian Smail for correspondence on optical identification of submm sources, Axel Weiß and Andrew Baker for comments on the text and Sergio Martin for an electronic version of the NGC 253 spectrum.

References

Aalto, S., Polatidis, A. G., Hüttemeister, S., & Curran, S. J. 2002, A&A, 381, 783
Aretxaga, I., Hughes, D. H., Chapin, E. L., Gaztañaga, E., Dunlop, J. S., & Ivison, R. J. 2003, MNRAS, 342, 759
Barvainis, R., Maloney, P., Antonucci, R., & Alloin, D. 1997, ApJ, 484, 695
Bennett, C. L., et al. 1994, ApJ, 434, 587
Benz, A. O., Grigis, P. C., Hungerbühler, V., Meyer, H., Monstein, C., Stuber, B., & Zardet, D. 2005, A&A, 442, 767
Carilli, C. L., & Yun, M. S. 1999, ApJ, 513, L13
Carilli, C. L., & Yun, M. S. 2000, ApJ, 530, 618
Carilli, C. L., et al. 2005, ApJ, 618, 586
Chapman, S. C., Blain, A. W., Ivison, R. J., & Smail, I. R. 2003, Nat, 422, 695
Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, ApJ, 622, 772
Greve, T. R., Ivison, R. J., & Papadopoulos, P. P. 2003, ApJ, 599, 839
Greve, T. R., Ivison, R. J., & Papadopoulos, P. P. 2004, A&A, 419, 99
Hughes, D. H., et al. 2002, MNRAS, 335, 871
Johansson, L. E. B., et al. 1984, A&A, 130, 227
Klamer, I. J., Ekers, R. D., Sadler, E. M., Weiss, A., Hunstead, R. W., & De Breuck, C. 2005, ApJ, 621, L1
Luhman, M. L., Satyapal, S., Fischer, J., Wolfire, M. G., Sturm, E., Dudley, C. C., Lutz, D., & Genzel, R. 2003, ApJ, 594, 758
Maiolino, R., et al. 2005, A&A, 440, L51
Malhotra, S., et al. 2001, ApJ, 561, 766
Martín, S., Mauersberger, R., Martín-Pintado, J., Henkel, C., & García-Burillo, S. 2006, ApJS (in press, astro-ph/0602360)
Ott, J., Weiss, A., Henkel, C., & Walter, F. 2005, ApJ, 629, 767
Riechers, D., et al. 2006, ApJ, in press
Schieder, R., Rau, G., & Vowinkel, B. 1986, Proc. SPIE, 598, 189
Solomon, P. M., Downes, D., & Radford, S. J. E. 1992, ApJ, 387, L55
Solomon, P., Vanden Bout, P., Carilli, C., & Guelin, M. 2003, Nat, 426, 636
Stacey, G. J., Geis, N., Genzel, R., Lugten, J. B., Poglitsch, A., Sternberg, A., & Townes, C. H. 1991, ApJ, 373, 423
Stanko, S., Klein, B., & Kerp, J. 2005, A&A, 436, 391
Walter, F., Carilli, C., Bertoldi, F., Menten, K., Cox, P., Lo, K. Y., Fan, X., & Strauss, M. A. 2004, ApJ, 615, L17
Vanden Bout, P. A., Solomon, P. M., & Maddalena, R. J. 2004, ApJ, 614, L97
Weiß, A., Henkel, C., Downes, D., & Walter, F. 2003, A&A, 409, L41
Weiß, A., Downes, D., Henkel, C., & Walter, F. 2005, A&A, 429, L25
Weiß, A., Downes, D., Walter, F., & Henkel, C. 2005, A&A, 440, L45